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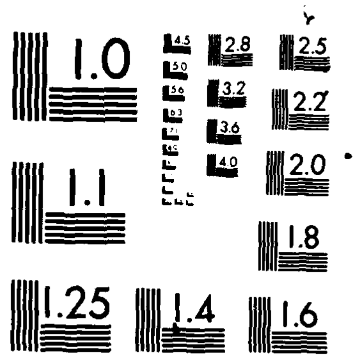

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A FUNDAMENTAL STUDY OF JET FLOWS

by

David Nixon

This report covers the period
March 1, 1982 to February 28, 1985

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Prepared Under Contract No. F49620-82-C-0031

for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
Bolling Air Force Base
Washington, DC 20332

by

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The object of the work is to investigate the fluid mechanics of impinging jet flows and to this end a combined theoretical, computational and experimental study was initiated. A very detailed set of experimental results for multiple impinging jets in a crossflow is available. The theoretical and computational study is concerned partly with modeling of the turbulence. An important result is that it appears that even the most sophisticated turbulence model available will not reproduce the experimental results adequately.

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ABSTRACT

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A FUNDAMENTAL STUDY OF JET FLOWS

RESEARCH OBJECTIVES

In the context of the jet fluid mechanics problem, there are two areas where present knowledge is incomplete. First is the fundamental behavior of the turbulent flow at the point where the jets impinge on the ground and where the wall jets produced by the jets collide. Related to this area is the detailed behavior of a wall jet flow colliding with a crossflow. The second area is the more applied aerodynamic problem of the effect of various parameters of the fluid motion and the stability of such flows. Typical problems that must be investigated concern the effect of Mach number and realistic temperature (2000°F) on the flow, and heat transfer, both on the ground and at the aircraft itself. It should be noted that each of the jets may have widely differing exit conditions. The combination of these flow parameters with crossflow is also an important problem. Also, certain configurations of jet and the ground may give rise to time-dependent flows or instabilities. The ultimate objective of the contract is to develop an understanding of both of these areas.

Each of the two areas noted above were investigated in a different manner. There is really no practical alternative to careful, detailed, experimentation to understand the turbulent processes in the impingement and fountain regions for single or multiple jets both with and without crossflow. Mach number and temperature effects were also being considered in this investigation.

For the second area, the best approach was to develop a computational model, since there are so many parameters in these flow configurations that an experimental program would be very costly. However, existing computational models are not adequate for two reasons. First, the turbulence model may be fairly primitive since it does not take account of changes in structure in certain regions of the flow. Second, the flow will be three-dimensional, compressible, and probably in some instances, unsteady. Thus the initial program consisted of the performance of a detailed set of experiments for certain impinging jet problems and the assembly of a computer code that solved the three-dimensional unsteady Navier-Stokes equations. An essential part of the latter task was the confirmation or, if necessary, the replacement of current algebraic stress equation turbulence models to represent the impinging jet flow fields. In addition to these tasks an analytic investigation was initiated to determine scaling laws for hot/cold jet experiments. This task was terminated in January 1983. A more detailed description of the research objective is given below.

COMPUTATION PROGRAM

The basis of the computer code used in this program was a code developed by Dr. Alan Wray of NASA/Ames Research Center for a free jet. This code was optimized for use on a vector computer and solved a "Large Eddy Simulation" (LES) approximation to the unsteady compressible Navier-Stokes equations. The subgrid scales were modeled by an algebraic turbulence model. The code used the Richtmeyer version of the Lax Wendroff predictor corrector algorithm.

In the development of the computer code the first step was to insert the ground plate and to test the code for either a laminar flow or turbulent flow using a simple model. The algorithm was changed to the 1981 MacCormack explicit/implict scheme. A turbulence model was necessary for the impinging jet case because computer limitations prohibited the use of the code in its LES mode. The code was then developed to treat multiple jets in a crossflow. There were essentially changes in the boundary conditions.

In parallel with the development of the code to treat impinging jet flows, the ability of algebraic Reynolds stress turbulent models to represent impinging jet flows was determined under subcontract. When a suitable turbulence model was verified it was inserted into the code. Initially an incompressible turbulence model was used; later work involved the use of a compressible model.

It should be noted that the production of this computer code was not an end in itself, rather it was simply a means of investigating the physics of jet flows more economically than an experiment.

EXPERIMENTAL PROGRAM

The experimental program was designed to provide information about the turbulence quantities in impinging jets. Specifically, mean-flow and turbulence measurements were made in impinging jets in the presence of an external stream to provide data for developing and testing turbulence models. It was believed that no turbulence model other than the full time-dependent Navier-Stokes equations was likely to be universally valid, so that empirical input had to be tailored to the flow type as suggested by Kline at the AFOSR-HTTM-Stanford meeting, and that only a fairly advanced model, relying on measurements of higher-order turbulence quantities, was likely to be useful in highly-three-dimensional flows like impinging jets. In particular, data for use in model development had to include all components of the Reynolds stresses and at least some of the mean triple products of fluctuating velocities, so that all the terms in the Reynolds-stress transport equations could be evaluated.

Measurements were made in the flow fields of either one or two jets, which emerged from one wall of a wind-tunnel working section and impinged on the other wall. The tunnel had a 45 in. wide, 72 in. long impingement wall, the 1 in. diameter jet nozzles being mourted in the opposite wall at a distance of 30 in. from the first. The jet speed was fixed at 180 ft/sec--the flow being effectively incompressible--and the tunnel speed could be continuously adjusted between 0 and 20 ft/sec. The proportions were chosen so that the interesting part of the impingement region was unaffected by the presence of the side walls, and the <u>maximum</u> tunnel speed was high enough for the jet to be deflected nearly horizontally before encountering the impingement wall. Thus a wide range of conditions could be covered. Hot wires were used for most of the measurements, with frequent calibration checks to ensure the accuracy of mean-velocity data in particular.

TURBULENCE MODEL

The approach used in the investigation of the turbulence model was to test the ability of three turbulence closures to represent an axisymmetric impinging jet flow. The three models were an eddy viscosity, "$k-\varepsilon$" model, an algebraic Reynolds stress model, and a full Reynolds stress model. Initially these models were tested for incompressible flow with the later work considering compressible flow.

FINAL STATUS OF RESEARCH WORK

COMPUTATIONAL PROGRAM

Nielsen Engineering & Research, Inc.

The principle focus of this work was to study the physics of impinging jets via numerical simulations based on the Navier-Stokes equations. In particular it was important to study phenomena not easily examined by research programs being conducted elsewhere. Some of these phenomena had long defied understanding and turbulence modeling; among these were the enhanced spreading of an upwash fountain and the Reynolds number scaling of the "suck down" effect.

While these are some of the key scientific questions regarding impinging jets, they are difficult to study using a Reynolds averaged Navier-Stokes approach. For example, the k-ε turbulence model has no mechanism by which the scaling of the "suck down" effect can be modeled. The high spreading rate of the fountain can only show up in the calculations if it is due to mean motion of the fountain, since it is not predicted by the turbulence model.

The validity of any numerical simulation is dependent on the accuracy with which the governing equations are solved. In particular, questions regarding the magnitude of the numerical viscosity and the asymmetry in the MacCormack (1981) algorithm were addressed. In fine grid calculations of a single impinging jet and the collision of two wall jets, the numerical viscosity was negligibly small except in the regions of very large velocity gradients at the wall. There the numerical viscosity was small relative to the eddy viscosity, but not negligible. Asymmetry in the algorithm was examined and found to be negligible except at the first grid point or two nearest to the wall. These points, which experienced small asymmetry (less than 10% in the solution updates), were adversely affected by the lack of proper numerical boundary conditions in the 1981 implicit MacCormack algorithm. With small time steps the asymmetry became quite small. In general the effects of the asymmetry were confined to the very near-wall region.

The following steps were undertaken in the quest to understand more about impinging jets.

1) The algebraic stress turbulence model (ASM) of Launder was incorporated in the computer code. This type of model was thought to be capable of predicting some of the complex turbulence phenomena that may occur in impinging jets, such as curvature. The experience gained during the present contract indicated that this model does not give a significant improvement, when compared to the k-ε model, for the complex turbulence phenomena of interest. Furthermore the ASM is both more expensive to use (roughly doubling the CPU time of the code), and less stable than the k-ε model.

2) Numerical simulations of two impinging jets with an upwash fountain were conducted. The response of the upwash to unsteadiness of the impinging jets was studied to determine whether the fountain made a flapping motion that contributed to the rapid spreading of the fountain. The results were that oscillations of the fountain decayed rapidly and it is believed that large scale motion of the entire fountain is not a mechanism that contributes to the enhanced spreading rate.

In summary, a computer code capable of simulating multiple, three dimensional, compressible impinging jet flows has been written and tested. While general flow features can be predicted, there are a class of problems that the numerical simulation cannot treat conceptually such as the enhanced spreading rate of the fountain. The state of the art of the computations is summarized in Reference 1.

EXPERIMENTAL WORK

Imperial College of Science & Technology, London

KEY RESULTS

The essential object of the work was to provide understanding, and detailed data, for use in calculation methods. It was anticipated that only methods based on the complete Reynolds stress transport equations would be adequate, and therefore as many terms in those equations as possible were measured. These are also the quantities needed to provide understanding, and this review concentrates on qualitative features.

(a) Flow Structure - The well known bent-over vortex pair, essentially trailing vortices due to the lift of the jet (Reference 2), behaves after impingement like a vortex pair with "common flow" towards the surface. A horseshoe vortex, formed mainly of boundary layer fluid, wraps around the front of the jet in the recirculating case. There is only a very shallow recirculating region confined within the thickness of the oncoming boundary layer, and the horseshoe vortex legs amalgamated quickly with the bent-over vortex pair, which rotates in the same sense.

The results emphasize the not quite obvious fact that the horizontal component of jet velocity relative to the oncoming stream is small almost everywhere. In still air, an impinging jet would spread equally upstream and downstream, but in a cross-flow the bifurcation is less strong and most of the jet fluid is moving downstream before it encounters the impingement pressure peak. Thus instead of the pressure gradient deflecting some fluid upstream and some downstream, it acts mainly on downstream-going fluid, producing consecutive retardation and acceleration with little net change in speed. Thus the velocity field near the ground in no way resembles a superposition of a cross-stream and an impinging jet in still air.

The shape of the impingement region changes rapidly with jet-to-crossflow velocity ratio in the range where separation is just beginning - that is, once the impingement region of high surface pressure has moved forward enough to produce a net upstream acceleration of some fluid, the further movement needed to deflect a large fraction of the mass flow rate upstream is quite small.

The above interpretations would still be valid in an inviscid flow; turbulence, as usual, causes complications. Turbulence significantly influences the "recirculation" process in which upstream-going fluid is swept back into the jet, and dominates the flow downstream of the jet where the vortex pair continues to distort the boundary layer. Another not quite obvious phenomenon, this time attributable to turbulence, is the tendency of a pair of jets, separated by a few nozzle diameters in the streamwise direction, to be sucked together by mutual entrainment. This produces the odd effect that adding a second jet downstream of the first <u>increases</u> the deflection of the upstream jet.

A crude estimate of the distortion of turbulence structure comes from assuming that the stress tensor and other vectorial quantities are simply rotated by the mean vorticity, specifically by the streamwise vortices generated in the bent over jet. Detailed results show more subtle changes, but even the crude model shows that, over the length of flow explored here, the stress tensor is rotated through 90 deg. so that the shear stress which originally produced mixing in side view (-uv) finally produces mixing in plan view (-uw). Similar effects of rotation are seen in the triple products, but would not be represented by the eddy diffusivity formulas used in conventional turbulence models.

(b) Instrumentation - Turbulence affects instruments intended to measure mean quantities: in a subsidiary project carried out by two French exchange students, different methods of measuring stress surface shear stress have been compared and shown that the simplest, the Preston surface pitot tube, is also the most useful in practice because its response is more nearly linear than that of a sublayer pitot tube or a sublayer hot wire. However, this near-linearity is found only for positive shear stress - that is, the probe must be pointed upstream, if necessary by doing two runs with the probe pointing in opposite directions.

A non-negligible contribution of the present work has been the development of a traverse gear with four microcomputer-controlled degrees of freedom (vertical position, pitch angle, yaw angle and roll) so that a hot wire probe can be aligned with the local flow direction and then rolled to resolve different velocity components. Spanwise position is adjusted manually by sliding a floor plate, streamwise position by interchanging floor plates. This traverse gear is much superior to any commercial "robot arm" and a duplicate has now been made for another project (the investigation of artificially generated longitudinal vortex pairs sponsored by NASA Ames). The microcomputer system used for control is also fairly advanced, using an 8-bit machine for data logging under control of a 16-bit machine to which the data are then passed for analysis.

PROBLEMS UNCOVERED

Like all experimental programs intended to provide aid for calculation methods, the present work revealed further problems. The inadequacy of current turbulence models was shown by the deficiencies in detailed agreement between experiment and calculation, but further work is in progress. The present data seem adequate for test purposes, but it would be helpful to have further experimental work with a larger recirculation region, preferably in a larger wind tunnel to minimize wall constraint. In the longer term, large eddy simulations of simplified versions of the flow would be highly desirable to give data on the pressure fluctuations. (The experimental data include all other major terms so that the terms containing pressure fluctuations can be deduced by difference, but this does not help very much in understanding the behavior of those terms).

A problem which was foreseen, but whose magnitude was underestimated, is the large amount of work needed to present the results of a three dimensional experiment graphically. Even the problem of drawing contour lines through data in a given cross sectional plane is non-trivial, vitually all computerized contouring routines having interpolation algorithms which produce unphysical, or merely implausible curves through data which are necessarily sparse. We feel that a real effort, possibly led by an agency, is needed to rationalize data presentation for aerodynamic experiments, which is just as important, and almost as costly in computer time, as flow calculations. (The problem of presenting the output of flow calculations is only a subset of the data presentation problem - for example, the convention is that calculations are presented unsmoothed.)

The measurements have helped to clarify the problems of three dimensional turbulent flows with strong streamwise vorticity, a subject which is now attracting much attention - examples include high angle of attack aerodynamics (especially strake flows), flow over ships ("bilge vortices"), and almost all flows over ground-mounted obstacles (such as the tendency of vortex pairs behind buildings to transport smokestack effluent towards the ground).

TURBULENCE MODELING

University of Manchester, Institute of Science and Technology (UMIST)

The aim of the UMIST work was to provide numerically accurate solutions of the Reynolds equations for complex jet-flow configurations to allow the capabilities of different levels of turbulence models to be assessed.

When the work began, scarcely any convincingly grid-independent results were available for turbulent elliptic flow. It had become clear that some alternative to conventional upwind-differencing would have to be adopted if the implications of the physical model were not to be obscured by numerical diffusion. A wide range assessment was thus undertaken (Reference 3) to ascertain which of several alternatives available provided the best scheme for approximating convective transport. Leonard's quadratic-upwind scheme, QUICK, gave the best overall performance.

The next task was to provide a computer program to facilitate the study of various turbulent flows. Although putting the QUICK scheme into one of the available off-the-shelf elliptic solvers was considered, there were so many additional refinements that should be included that it was decided to write a new code-TEAM, (Turbulent Elliptic Algorithm - Manchester). This is believed to be the first general-purpose elliptic code to be made available that contains an algebraic stress model of turbulence (ASM). A user's guide has been written to facilitate transfer (Reference 4).

In parallel with the above work, a study of the near field of high temperature axisymmetric jets was undertaken using, in this case, a parabolic solver (i.e. one in which the pressure was taken as uniform across the shear flow (Reference 5). An ASM was adopted for the turbulent stresses and heat fluxes including the effects of density fluctuations. From this it emerged that the effects of density flucutations per se on the mean flow were short-lived - at most 10 diameters; even in the initial region the effects were of only moderate significance. This was a helpful discovery because the very many extra fluctuating-density products in the turbulence model greatly complicated the solution - even for a parabolic flow. Accordingly, in the subsequent studies of elliptic (impinging and recirculating) jets only uniform-density forms of the turbulence model were considered.

A further discovery made from examining 'parabolic' jets, however, caused some delay in tackling the cases of elliptic flows that were of primary interest. This was that substantial differences in the predicted rate of spread of various jets converged depending on whether an ASM or a full Reynolds stress solver (RSTM) was used. This discovery (Reference 6) was surprising as it had not been previously reported in over 10 years of testing ASMs and RSTMs. Evidently jet flows are particularly sensitive to the simplifications in the physical model implicit with the ASM truncation.

The above discovery meant that the much more complicated impinging jets should be computed with a full Reynolds stress solver. The TEAM code was therefore extended to incorporate such a model. Although superficially straightforward, this extension of the code proved to be rather difficult to secure convergent behavior. Eventually a reliably stable set of procedures was devised (Reference 7).

Attention was thereafter focused on the selected group of impinging jets. One striking and not entirely expected feature was the sensitivity of the results to the boundary conditions on the mean velocity field applied at a quiescent (entraining) boundary. The problem becomes increasingly severe as the level of the turbulence model is raised. The best constraints, from a physical point of view, that the entrained fluid should have a prescribed stagnation pressure and zero vorticity, prove to be unstable with other than the k~ε EVM and, in the case of two colliding wall jets (Reference 8), even with that model.

Satisfactorily grid-independent computational results of all the test flows except the colliding wall jets were achieved with all three levels of turbulence model, i.e. EVM, ASM and RSTM. Grids as fine as 100 x 100 were used in one case to confirm grid independence, but for the remaining cases typical mesh densities were around 40 x 50.

For the case of the Castro-Bradshaw strongly curved mixing layer, the results indicated that the suppression of turbulence due to streamline curvature was fairly well predicted by the standard k~ε EVM, this model reproducing about 70% of the reduction in turbulence energy levels measured by the experimenters. The two higher order models gave a too strong suppression of turbulence. This result was an unexpected development. For weak curvature it is known that EVM approaches show far too little sensitivity to the extra strains associated with streamline bending; in such cases, ASM or RSTM schemes do much better. So far as the physics are concerned, the implication seems to be that the selective augmentation or damping of velocity fluctuations by the extra strains (an effect that is captured exactly by the ASM and RSTM approaches) is offset, when the extra strains are large, by a more effective redistribution by the action of fluctuating pressures.

Results for the colliding wall jets are not yet definitive due to the difficulty with boundary conditions noted above. The indication seems to be, however, that the predictions do not reproduce the strongly augmented rate of growth of the upwash that experiments display. The problem seems to be associated with the ε equation which essentially determines the length scale. In simple physical terms, the length scale seems to double in width as the two shear layers impact on one another.

Overall the research has made a number of contributions to numerical aspects of computing turbulent flow from the averaged Navier-Stokes equations. It has also highlighted some not entirely resolved problems in these areas. The picture concerning the physics - the turbulence modeling - is much less clear-cut. Two points of ideology have been overturned: firstly, the idea that in thin shear flows the ASM and RSTM give essentially the same results; secondly, the view that an EVM will always do worse than either an ASM or RSTM in predicting the effects of streamline curvature. Finally, the shortcomings in predicting the growth of the upwash of colliding wall jets point to a fundamental weakness in the ε equation that mere tinkering with extra coefficients is unlikely to remove.

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7. Huang, P. G. and Leschziner, M. A.: Stabilization of Recirculating Flow Computations Performed With Second-Moment Closures and Third-Order Discretization. Proc. 5th Turbulent Shear Flows Symposium, Cornell, August 1985.

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1. Huang, P. G., Launder, B. E. and Leschziner, M. A.: The Discretization of Non-Linear Convection Processes: A Broad-Range Comparison of Four Schemes. Comp. Meth. in Appl. Mech. & Engrg., 48, 1, 1985.

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10. Shayesteh, M. V. and Bradshaw, P.: Microcomputer Controlled Traverse Gear for Three Dimensional Flow Explorations. To be submitted for publication.

11. Shayesteh, M. V., Shabaka, I. M. M. A. and Bradshaw, P.: Turbulence Structure of a Three Dimensional Impinging Jet in a Cross stream. AIAA Paper 85-0044, 1985.

PERSONNEL

The above program is being performed by several organizations under the general direction of Nielsen Engineering & Research, Inc., with Dr. David Nixon as Principal Investigator. The various topics with the appropriate organizations are given below.

1. Computational Program - Nielsen Engineering & Research, Inc. (Dr. David Nixon and Dr. Robert E. Childs)

2. Experimental Program - Imperial College, London. (Prof. Peter Bradshaw and Mr. Massoud Shayesteh)

3. Turbulence Modeling - University of Manchester Institute of Science and Technology (UMIST). (Prof. Brian Launder, Dr. Michael Leschziner, and Mr. George Huang)

THESES

1. Huang, P. G.: The Numerical Prediction of Impinging and Recirculating Jet Flows with a 2nd-Moment Turbulence Closure. PhD Thesis, Faculty of Technology, University of Manchester (to be submitted July 1985).

2. Shayesteh, M. V.: Part of the work on the contract will be incorporated into a PhD. thesis for the University of London.

PRESENTATIONS

1. Alternative Schemes for Discretizing Steady Convection. Computational Fluid Mechanics Colloquium, UMIST, April 1984.

2. Solution of the Algebraic Stress Model Equations for Elliptic Flows. Computational Fluid Mechanics Colloquium, UMIST, April 1984.

3. The Computation of Jets at High Temperature and Mach Number. Computational Fluid Mechanics Colloquium, UMIST, April 1984.

4. 9th Meeting of IAHR Working Group on Refined Modeling of Flows. Aix-en-Provence, France, January 1985.

5. Study of Impinging Turbulent Jets. AIAA Aerospace Sciences Conference, Reno, NV, January 1985.

6. Turbulence Structure of a Three Dimensional Impinging Jet in a Cross Stream. AIAA Aerospace Sciences Conference, Reno, NV, January 1985.

NEW DISCOVERIES

The new discoveries are contained in the section "Final Status of Research Work". There were no inventions or patent disclosures resulting from the work.

END

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